Entropy of the EEG Signal is a Robust Index for Depth of Hypnosis

H. Viertiö-Oja, PhD, M. Särkelä*, MSc, P. Talja, MSc,
H. Tolvanen-Laakso, MSc, and A. Yli-Hankala**, MD
Datex-Ohmeda Div., Instrumentarium Corp., FIN-00031 Datex-Ohmeda, Finland
*Check address, FIN-90210 Oulu, Finland
** Dept of OB-GYN, HUCH, FIN-00029 HYKS, Finland

The complicated neural behavior of the brain manifests itself in the non-analytical, non-linear, non-stationary, and fractal dynamics of the EEG signal. We have applied a collection of mathematical techniques to extract the relevant information that discriminates between different hypnotic depth levels. The EEG signal was measured during 150 anesthesia cases with propofol, sevoflurane, and/or N_2O. Depth of anesthesia was tested and classified to six OAAS (observer's assessment of alertness and sedation) levels by an anesthesiologist. The following characteristics of the EEG signal were analyzed: 1) standard spectral features, 2) bispectrum [1], 3) burst suppression ratio, 4) fractal spectrum [2], 5) Lempel-Ziv complexity [3], 6) approximate Kolmogorov-Sinai entropy [4], and 7) spectral entropy [5]. In this study, fractal spectrum and Lempel-Ziv complexity were investigated for the first time in anesthetized humans. Combinations of the calculated parameters were analyzed using neural networks.

We found that the fractal power spectrum obeys a frequency power-law $1/f^{\beta}$, where the fractal exponent β increases consistently in the course of deepening anesthesia. The transition between consciousness and unconsciousness (OAAS levels 3 and 2) takes place at a critical value of β which is independent of the patient.

Analysis of spectral entropy, approximate Kolmogorov-Sinai entropy, and Lempel-Ziv complexity involves a choice of the time scale at which the variations of the EEG signal are analyzed. We found that if the time scales are selected consistently, all the three parameters of disorder show similar behavior. In the following discussion, "entropy" refers to our results computed for the spectral entropy of the EEG signal. Our principal findings are the following: 1) Entropy behaves monotonously as a function of anesthetic depth at all levels from light sedation down to burst suppression. 2) Transition from consciousness to unconsciousness takes place at a critical level of entropy which is independent of the patient. 3) Recovery of consciousness in the end of anesthesia can be predicted by a gradual rise of the entropy towards the critical level.

The EEG signal collected for our analysis was simultaneously directed to a Bispectral Index (BIS) Monitor (Aspect Medical Systems). We also calculated the three components of BIS: the bispectral parameter SynchFastSlow, the BetaRatio, and the burst-suppression ratio [1]. We were thus able to make direct comparison of entropy, BIS, and its three components.

According to our results, entropy and BIS follow each other closely in the intermediate levels of anesthesia. In this region, BIS varies according to its bispectral component SynchFastSlow. When a patient is anesthetized, relative reduction of the quadratic phase coupling at the high frequency range, indicated by SynchFastSlow, takes place. As a result, the spectral reserve and, consequently, the entropy are reduced. Bispectral analysis thus assesses a particular mechanism that contributes to decrease of entropy during anesthesia.

Marked differences between the approaches employing entropy and bispectrum are discovered at the two endpoints of the hypnosis scale: at light sedation and in deep

anesthesia. The bispectral parameter SynchFastSlow is often found to increase in the beginning of induction before it starts to decline according to deepening hypnosis. In order to obtain a monotonously decreasing BIS value, the information of BetaRatio has to be included. The bispectral parameter SynchFastSlow also fails to give consistent results in deep anesthesia when burst suppression sets in. For this reason, explicit information of burst suppression is required for computations of BIS. No such adjustments are necessary for entropy, neither in weak sedation nor in deep hypnosis: entropy varies monotonously as a function of anesthetic depth at all levels.

Recent theoretical work on a microscopic model of the neural system [6], together with experimental findings [7], may provide a natural explanation for the relation of entropy and depth of anesthesia. The results point to the conclusion that when an anesthetized patient loses consciousness, a thermodynamic phase transition of the neural system takes place, analogously to the transition that occurs when water freezes into ice. The removal of latent heat corresponding to such a transition has been observed in anesthetized patients as diverging EEG power [7]. According to thermodynamics, the conscious and unconscious states of the brain should thus have distinct values of entropy.

References

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